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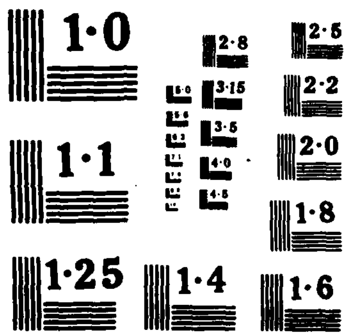
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FINAL REPORT

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TITLE: **EFFECTS OF STATIC LUNG LOADING ON CARDIORESPIRATORY FUNCTION IN SUBMERGED EXERCISING SUBJECTS AT DEPTH**

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TABLE OF CONTENTS

6

Letter on file

A-1

SCIENTIFIC BACKGROUND OF THE CONTRACT

Work by Other Researchers

The overall rationale for the work performed under this contract was that an important aspect of man's usefulness under water is the ability to perform physical work. Compared to terrestrial conditions the diving environment often restricts this ability. The primary limitations to submerged work appear to be cardiorespiratory. This notion is supported by investigations in which exercise at depth was limited by dyspnea, i.e. shortness of breath (1a-3a). Several potentially important factors behind this dyspnea could be envisioned. These factors were:

(1) increased respiratory flow resistance due to high gas densities at depth

(2) resistance in the diver's breathing gear

(3) static lung loading due to depth differences between the divers chest and his breathing gear.

While these three factors had all separately been subject to some study earlier it was evident from the literature that their relative importance had not been assessed under conditions resembling actual diving.

The effects of increased gas density on pulmonary function were well known. Restrictions of gas flow are reflected in maximal voluntary ventilation, forced expiratory and inspiratory flows, and increased work of breathing as well as a tendency to hypoventilation (e.g., 4a-12a). These restrictions may be further exacerbated by resistances imposed by the breathing apparatus (13a-16a). The effects of gas density had mainly been studied in dry simulated dives. The applicability of these studies to the submerged diver, especially during exercise, was questionable because of the additional physiological effects of

immersion. Immersion induces static loads on the chest (positive or negative pressure breathing) with consequences that have been investigated by several authors. The lungs of the diver may be exposed to a wide range of negative and positive intrapulmonary pressures depending on body position in the water and type of breathing apparatus. Nevertheless, most experimental studies had been done in the upright head-out position (yielding negative intrapulmonary pressures) because of the methodological difficulties in working with fully submerged subjects. Respiratory changes in this situation include decreased vital capacity and functional residual capacity, a more even regional pulmonary perfusion, and increased pulmonary air trapping (17a-26a). The circulation is also influenced in that intrathoracic blood pooling occurs causing increased cardiac output and peripheral perfusion (27a-29a). These studies had, however, all been made in the resting subject. Very few physiological studies had attempted to elucidate specific immersion effects on the working diver and they had apparently all been made at 1 ATA in head-out immersion or with the subject immediately under the surface.

In a classical study by Paton and Sand in 1947, completely immersed subjects were exposed to various static lung loads (30a). It was determined that the breathing gas pressure most conducive to comfort in the erect subject corresponded to the water pressure 5 to 10 cm below the ear opening. In the prone, supine, and head-down erect positions, the eupneic pressure point was at the suprasternal notch. In erect subjects, respiratory stimulation by carbon dioxide admixture to breathing gas or by maximal physical exertion resulted in an increase in eupneic pressure of up to 10 cm H_2O. The introduction of external breathing resistance on the expiratory side tended to decrease the eupneic pressure; inspiratory resistance caused an increase in eupneic pressure. With regard to static loads (i.e., imposed deviations from eupneic pressure), positive pressure was subjectively more acceptable than negative pressure and, in general, departures from eupneic pressure were best tolerated in the horizontal position. However, limits of tolerance (30 cm H_2O greater and 25 cm

less than eupneic pressure) were only tested during short exposures and the authors stated that exercise or longer exposures would undoubtedly have lessened the range which was tolerable. Despite the clear-cut subjective effects of static lung loading, there were, however, no changes in pulmonary ventilation or oxygen consumption.

Denison et al. (31a) studied exercising fully immersed subjects. No special immersion effects were seen in oxygen consumption or cardiac output, although, at a given oxygen consumption during immersion, the heart rate was slightly elevated as was alveolar carbon dioxide tension (at moderate work rates). However, no static load was imposed since the breathing gas pressure was set at the eupneic pressure point.

Another attempt at elucidating immersion effects on working subjects was made by Dressendorfer et al. (32a). This study was performed at 1 atm during head-out immersion while pedaling on a bicycle ergometer. Slight decreases in maximal oxygen consumption and ventilation were observed which were ascribed to immersion. Again, no attempt was made to vary the static load during immersion. A study by Fagraeus and Bennett (33a) was unique in that the fully immersed subjects performed arm exercise. They were dressed in conventional dry suit and helmet. Immersion produced a decrease in heart rate, but increased gas density (up to 19.16 atm, 7% O_2 in helium) did not affect it. However, ventilatory response to exercise was decreased by increased gas density. The experimental technique (unspecified degree of suit inflation) did not allow the static load to be defined in these experiments.

During a dive to 49.5 atm by the Navy Experimental Diving Unit (3a), completely immersed, sitting divers performed graded leg exercise while breathing from a modified Navy closed circuit diving apparatus. These divers suffered incapacitating dyspnea while exercising at moderate rates (25 - 50 watts, oxygen consumption 1.80 - 1.92 l/min). Arterial blood analyses showed no

hypoxia, hypercapnea, or acidosis. The pressure fluctuations at the mouth were low, indicating that flow resistance in the breathing apparatus was probably not the cause of the dyspnea. However, the breathing bags were situated at the shoulder level so as to expose the diver to a negative static load. No attempt was made to evaluate the effect of this static load. It is important, though, that these divers were able to sustain much higher work rates (up to 125 watts) at shallower depths (10 atm) using the same experimental configuration. Studies during dry simulated dives employing similar gas densities had indicated a much higher exercise tolerance (33a-37a), and, therefore, it seemed that combination of negative static lung load and high gas density acting on the lungs interfered with diver performance at the deepest depth in the study by Spaur et al (3a).

STUDIES DONE IN THIS LABORATORY

Earlier Work

The limitations of previous studies underscored the need for investigating the completely immersed exercising diver under conditions in which gas density, static lung loads, work rate, external breathing resistance, gas composition, and temperature could be controlled independently and systematically. To this end, a program was undertaken in June 1975 in this laboratory to study the effects of static lung loading on the cardiorespiratory function of immersed subjects unimpeded by the gas flow resistance usually imposed by breathing apparatus.

The unique design of the SUNY at Buffalo wet chamber with its dual barrier system lent itself to imposing well-defined positive and negative static lung loads on subjects performing underwater exercise. A special low resistance breathing system was designed which is compatible with the dual barrier system and allows monitoring of a variety of respiratory parameters. In addition, an electrically braked ergometer was waterproofed to be used for imposing

reproducible work rates on the subjects. These methodological innovations were published under an earlier contract (38a-39a).

The first series of studies focused on the effects of static lung loading in prone, exercising subjects, and ancillary problems. One of the major observations in this work was that static lung loadings in the range of -20 to +20 cm H_2O may have profound effects on a diver's ability to perform work under water. Negative static lung loads were associated with increased dyspnea (shortness of breath) which could be so severe as to become work limiting and even pose an increased risk of drowning in case of temporary breathing gear malfunction. By contrast, positive static lung loading tended to relieve dyspnea induced by work at depth, a +10 cm H_2O static load being particularly advantageous. These findings can be directly implemented in the design of breathing gear for divers so as to increase safety and efficiency in diving (40a).

Work Performed under the Present Contract

The program outlined above was succeeded by a new series of studies begun in 1978 under the Contract subject to this Report. These studies aimed at expanding the earlier contract and introducing additional stress factors that are unique to the diving environment.

While the study of static lung loading described above utilized leg work in the prone position (analogous to a swimming diver), a lot of under water work is also performed in the erect position. Because the hydrostatic pressure on the chest and extrathoracic airways is distributed differently in the erect position than in the supine, we felt it was important to determine if static lung loads would affect the upright diver differently.

An earlier study reported marked differences in relaxation pressures of the chests of immersed subjects in the upright position depending on whether breathing is via a face mask or mouthpiece (41a). While the face mask allowed the subject to relax against an overpressure (positive static lung load), use of the mouthpiece required sustained muscle tension. This muscle tension involves the chest wall and prevents relaxation. The breathing pattern of divers has been observed to be different when divers are connected to a breathing apparatus via a mouthpiece as compared to breathing free of any equipment (42a). Furthermore, we took note of a report of an increase in arterial P_{CO_2} and a fall in P_{O_2} in response to obstruction of nasal airflow (43a). We reasoned that hypoventilation induced in this way may, perhaps, also occur in divers using a mouthpiece because the ancillary face mask would prevent nasal breathing. Because divers use both full-face masks (or helmets) and mouthpieces, it was proposed that these two types of equipment be compared with regard to their effects on respiratory function in divers subjected to varying static loads. Because the static loads associated with the greatest differences between mouth pressure and ambient pressure would be encountered in the erect posture, this was the posture in the new studies. The fact that obstructed nose airflow may induce hypercapnia was thought to be of particular significance for divers, some of whom are known to have a tendency to accumulate CO_2 at depth for a variety of reasons. The present studies considered this problem as well.

The selection of the above mentioned problem areas was encouraged by discussions with a senior representative of the Navy Experimental Diving Unit. A sizable proportion of all military diving is done with mouthpiece equipment. In addition, we were informed that the use of diving equipment with mouthpieces may be preferable to equipment with full-face masks under certain circumstances. This is so because of the tendency for full-face masks to leak under high positive pressure loads, thereby making the disarming of acoustic mines more

dangerous. For these reasons it was considered desirable to determine optimal levels as well as tolerance limits for static lung loading during mouthpiece breathing.

The Findings

In keeping with the proposal's underlying Contract, two major studies have been carried out. In one, called "Respiratory Function in the Upright, Working Diver at 6.8 ATA (190 fsw)" (1b-5b), we investigated the influence of static lung loading on a number of respiratory parameters in subjects performing graded leg exercise in an upright posture while submerged and breathing air at ambient pressures up to 6.76 ATA. In comparison with a previous investigation of the prone posture, a lesser tendency to dyspnea was observed. Neutral and moderately positive static lung loads were associated with less dyspnea than were negative loads. Several indices of respiratory function remained relatively normal during exercise and exposure to varying static lung loads. However, there was a tendency for hypoventilation and CO_2 accumulation during heavy exercise at 190 fsw; this was not strictly correlated with dyspnea or static lung load.

We conclude that, if a full face mask is used, breathing gear for divers should provide a static lung load of approximately 0 to +10 cm H_2O regardless of the diver's orientation in the water. When possible, divers should assume an upright posture while engaged in strenuous work under water.

The other major study entitled "A Comparison of Pulmonary Function in Divers Breathing with a Mouthpiece or a Full Mask" (6b,7b) compared pulmonary function in submersed divers breathing with either a mouthpiece or a full face mask while exposed to varying depths (15 fsw and 190 fsw), exercise loads (0-175

watts), and static lung loads (0 and -20 cm H_2O). The breathing equipment was designed to be identical in terms of dead space volume and resistance to gas flow.

Use of a mouthpiece caused a modest fall in expired minute volume at both depths. The majority of this decline may be the consequence of a decrease in dead space ventilation brought about by the elimination of simultaneous nose-breathing and mouth-breathing. Alveolar ventilation and $P_{et}CO_2$ were not significantly influenced by the use of a mouthpiece regardless of depth, workload, or static lung load. Episodes of dyspnea were infrequent during experiments with a static lung load of 0 cm H_2O. Therefore, if a neutral static lung load is maintained, the type of breathing gear used does not appear to be of consequence as far as dyspnea is concerned.

In the course of pursuing the two major research projects mentioned above, some related, unanticipated questions arose which were addressed in separate studies. One was inspired by the observation that subjects performing exercise at depth appeared to have a larger vital capacity after a period of work than before exercise. The hypothesis tested was that this may have been due to peripheral vasodilatation due to increased thermogenesis and other factors related to the exercise. Indeed, it turned out that when subjects were exposed, in separate experiments, to water of different temperatures, cool water (20°C) induced a reduction in vital capacity of up to 15% compared to warm (37°C) water, apparently by causing more blood to be pooled in the thorax (8b). This observation forces one to conclude that immersion in itself is not sufficient to completely counteract the effects of normal gravity on the blood distribution in the body but that vasomotor tone still may exert an effect. A tentative extrapolation from this would be to suggest that contrary to "common wisdom", vasovagal syncope could occur during immersion in the upright, head out posture, given a sufficiently low vascular tone.

In some of our early studies of static lung load effects, we had recorded ventilation levels during heavy exercise that exceeded those measured during standard maximal voluntary ventilation tests (40a). This paradoxical phenomenon was studied further. We were able to demonstrate that exercise in itself while performed at depth, enhanced the ventilatory capacity. Thus, maximal voluntary ventilation and maximal expiratory flow measured during exercise at depth exceeded the values obtained during rest. These observations are of consequence for predictions of a diver's ventilatory capacity during diving, based upon conventional lung function tests.

Several methodologically important studies directly related to the theme of the current Contract were undertaken. In one, "Gas inertia and ventilatory measurements under pressure: methodological considerations", a potentially serious source of error in measurements of ventilatory volumes was identified, quantitated and remedial methodology described (9b). This study should be of interest to anybody doing respiratory measurements by directly recording gas flow.

A caliper for reduction of data from strip chart recordings in our dive experiments was deemed of sufficient usefulness to the research community to be described in an article in the Journal of Medical Engineering and Technology (10b).

Problems with inadequate frequency response in widely used polygraphs were identified in conjunction with the respiratory measurements under the Contract. These problems were subjected to scientific study and remedial measures described (11b).

During the Contract period a number of research projects and publications have been completed which received partial support, typically in the form of the use of research equipment acquired under this Contract. The subject areas

covered are illuminated by the titles in the list of references (12b-30b) and details are available in the enclosed reprints. All these projects, which were partially credited or will be credited to this contract, contain elements of interest to Navy diving. For instance, studies of the physiology of breath-hold diving may apply to the safety of the Navy diver should his breathing gear malfunction.

MILITARY SIGNIFICANCE

Investigations under the Contract have characterized several aspects of the cardiopulmonary function of divers utilizing conditions which closely reproduce open-ocean compressed air diving with regard to combinations of (1) submersion, (2) depth extremes as stated in the U.S. Navy Manual (maximum depth of 190 fsw), (3) dynamic exercise loads, (4) equipment-airway interfaces (mouthpiece vs. facemask breathing), (5) static lung loads, and (6) posture. The work under the Contract generated a number of scientifically significant observations which are detailed elsewhere in this document and its enclosures. However, the following observations and recommendations are highlighted as being particularly relevant to diving operations and equipment design:

Observations

(1) As compared with a previous study of the prone position, the upright posture was associated with a reduced incidence of dyspnea (shortness of breath) during heavy exercise at both shallow and extreme depths.

(2) Neutral and slightly positive static lung loads appeared to reduce the incidence of exercise-induced dyspnea at both shallow and extreme depths.

(3) The nature of the equipment-airway interface did not influence the incidence of dyspnea if a neutral static lung load was maintained.

(4) Exercise at extreme depths was associated with impaired pulmonary gas exchange which led to marked hypercapnea despite the fact that the experimental apparatus imposed a minimal breathing resistance. Carbon dioxide elimination was not further compromised by a particular static lung load, posture, or equipment-airway interface.

(5) Breath-holding endurance was drastically reduced by exposure to cold water (30b).

(6) Breath-hold duration in man was enhanced during submersion in thermoneutral water (35°C) by more than 25% compared to the non-immersed control situation (30b).

(7) Intrathoracic (esophageal) pressure fell on the average by 29 cm H_2O in non-immersed simulated breath-hold dives to 20 m and by 21 cm H_2O in submersed breath-hold dives to the same depth, apparently due to differences in intrathoracic blood redistribution (14b).

(8) Hyperbaric oxygen (3 ATA) administration to pregnant ewes caused a dramatic increase (6-22 fold) in pulmonary blood flow of the fetuses, simulating the circulatory adjustment at birth (29b).

Recommendations and Conclusions

Breathing gear for divers should provide a static lung load of approximately 0 to +10 cm H_2O regardless of the diver's posture in the water.

If a neutral static lung load is maintained, the choice of a full face mask or a mouthpiece is not constrained by physiologic concerns.

When possible, divers should assume an upright posture while engaged in strenuous work.

Equipment intended to be serviced by divers, and the tools they use, should be designed for the vertically oriented diver.

Because marked hypercapnea occurred during exercise at 190 fsw despite the use of breathing gear which imposed a minimal flow resistance, factors which can produce further hypercapnea (such as additional resistance in the breathing gear, increases in gas density or an individual's low respiratory CO_2 response) should be controlled in deep diving.

Emergencies such as breathing gear malfunction may be particularly hazardous in cold water because of its attenuation of breath-holding endurance.

The prolongation of the breath-holding time in water at 35°C may imply an increased risk for the thermally comfortable breath-hold diver to suffer dangerous hypoxia.

The larger intrathoracic pressure drop when simulated breath-hold diving is performed in the non-immersed than in the submersed mode suggests greater risk for thoracic squeeze in the former mode and a greater risk for circulatory overloading in the latter.

The strong vasoactive effects of hyperoxia on fetal lung circulation may have deleterious effects should a pregnant woman dive or otherwise be exposed to high oxygen tensions.

THE CONTRACT AND THE STATE OF THE LABORATORY

The work performed under the present Contract has greatly benefited from the fact that this laboratory is an integral part of the Department of Physiology, State University of New York at Buffalo. This Department has a tradition of research in environmental physiology especially as it pertains to extreme environmental pressures. This tradition was begun when Dr. Hermann Rahn became the Chairman of the Department. In recognition of his role in this regard, the School of Medicine recently named the laboratories housing the equipment, to which this Contract as well as earlier Navy support have contributed, the Hermann Rahn Laboratory of Environmental Physiology. Our close interaction with the Department has been important for the work under this contract in many ways.

First, there is the intellectual stimulation of the contact with over 30 physiologists doing full time research. Secondly, the logistic support that this Contract and the Department have exchanged has been to the benefit of both functions.

Because of a funding ceiling in the years 1982-1985, this program was not able to support a full sized dive crew for the chamber experiments. We were short one full time technician. However, because of the existence of a functioning compressor facility and gas mixing service which we had to keep running for our own needs, other programs within the Department could be offered certain critical help. We, in return, received help on dive days from a technician supported by other programs so as to make our intense dive schedule feasible. The experimental work under this Contract has caused us to perform a total of 1,593 recorded man dives corresponding to 3,004 man hours of time under pressure in the hyperbaric chamber.

The hyperbaric chamber crew has consisted of:

1. chamber operator
2. log keeper
3. inside (chamber) equipment operator
4. inside dive tender
5. outside equipment operator
6. outside experiment coordinator and medical safety officer

The persons fulfilling functions 1-5 have primarily been Mssrs. Bruce Laraway, Dean Marky, Ron Smith, Paul Simonetti and Andrew Barth; the researchers serving as coordinators during successive periods of the Contract have been Drs. Edward Thalmann, Donald Hickey, and William Norfleet.

In addition to the aforementioned direct personnel support for the execution of the experiments, our work has received help from the Department in the form of machine shop and electronic shop services for fabrication and maintenance of experimental equipment.

The confidence in this laboratory that the Naval Medical Research and Development Command has shown by awarding the Contract has, without doubt, been very important in attracting support from the University for our work. Thus, three major contributions to strengthen our research potential were granted during the last couple of years:

1. A $295,000 addition to our hyperbaric chamber laboratory was granted. This includes 1,100 sq. ft. of laboratory, a 1,250 sq. ft. compressor building and a gas storage pad. This is all new construction which has just been completed.

2. A $300,000 grant for completion of the life support system of our 170 ATA chamber has been awarded to us. This work which is in progress will provide all the technical facilities for the deepest saturation diving capacity of all chambers in this country. All systems are made to U.S. Navy standards.

3. The opportunity for competitive proposals for the establishment of a limited number of organized research centers was announced by the University in 1985. Our group was awarded $86,000/yr. for three years to set up a Center for Research in Special Environments. This Center, under the directorship of Dr. C. Lundgren, will provide the organizational framework to enhance effective use of the many unique research facilities within the Hermann Rahn Laboratory for Environmental Physiology. Particular emphasis will be placed on supporting multidisciplinary projects between physiology and engineering. Continuity in administrative and technical services will be enhanced by personnel employed on the Center budget.

We are looking forward with enthusiasm and confidence to a continued role in the University affiliated research of the U.S. Navy.

Buffalo, NY, June 20, 1986

Claes Lundgren

Claes Lundgren, M.D., Ph.D.
Principal Investigator

enclosures: Reprints/manuscripts,
1b - 30b, one set

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